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NUCLEAR POWER TECHNOLOGY AND COSTS

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I. Introduction

1. Nuclear power has now achieved a state of development and experience such that it warrants serious consideration in connection with planning future growth of power systems. There are undoubtedly many situations in the world in which a clear economic justification can be made for nuclear power plants. Likewise, of course, many situations which may appear to be favorable to nuclear power on the basis of a superficial analysis will not be economically favorable when the situation is analyzed in greater detail. Even in areas in which nuclear power does not appear to be economically justified at the present time there may be good reasons to gain some experience with nuclear power plants now in order to have a solid foundation upon which to build a nuclear power industry which will be economically attractive in the future. On the other hand, a premature or poorly directed nuclear power plant construction program can be wasteful of valuable national efforts.

2. It is the intent of this paper to review briefly the status of nuclear power plant technology based upon experience in the United States with particular reference to possible application of that experience to the needs of less developed areas. The definition of "less developed areas" is clearly a relative matter. Some areas of the United States, for example, are less developed than other areas. Thus, some evaluation of nuclear power for less developed areas can be made within national boundaries. Even more important, and certainly more complicated, is the evaluation of nuclear power for countries which are "less developed."

3. Nuclear power has many different energy applications. Its development thus far has been primarily for the production of electricity because this application requires relatively large plants that appear economically favorable to nuclear power. Production of electricity also appears to be the application of most immediate interest to less developed countries. Frequently the distinguishing features of such countries are relatively low per capita income and relatively low per capita consumption of electricity. This observation naturally leads to a common impression that there is a direct correlation between use of electricity and income. A closer look, however, shows that the correlation is not exact. Increased standards of living are not achieved simply by increasing electric power supply. A low ratio of electric power consumption per unit of national income, which is charateristic of less-developed countries, is the result of an interplay of many factors. These factors include, for example, limited or undeveloped resources, low industrialization with low power demands, and high fuel costs with high electric generating costs. Figure I (compiled from data given in the United Nations Statistical Yearbook, 1960) is an illustration of the irregular correlation and importance of these factors. Note that Canada, Norway and Japan all have higher rates

of electricity consumption per unit of income than the United States but their per capita incomes are lower. The general conclusion from such an evaluation of factors contributing to the state of development of an area is that availability and cost of fuel are very important.

4. Nuclear fuel has characteristics which make it unique for equalizing the cost of fuel in various geographical areas. It is natural, therefore, that countries which have been relatively slow in their development because of scarcity or cost of fuel look with interest toward nuclear power.

II. Status of Nuclear Power Technology

5. The results of research and development, design, construction and operation of nuclear power reactors in the United States have been widely reported.[1-10] This experience includes a wider range of reactor concepts than that of any other country. Nevertheless, the results of work in other countries also are very important and should be considered in the planning of any future program. The class of reactors using ordinary water as moderator and coolant has had the most extensive developmental support in the United States. There are several design variations within the class, extending from those which permit no net steam generation in the core to those which have all steam generated in the core and passed directly to the turbine. Variations in control scheme and fuel management also are available. The specific choice of design and mode of operation should depend upon the size plant required and other considerations related to the specific application including, of course, the financial arrangement offered for its construction.

6. In the United States current plant construction bids, fuel guarantees, and applicable government policies permit construction of plants in the range of a few hundreds of megawatts of electrical capacity which should be competitive with fossil fueled plants in areas where fossil fuel costs are 35¢ per million BTU and perhaps even slightly less. In general, the economics of nuclear plants relative to fossil fueled plants becomes less favorable as the plant size decreases. In other words, the fossil fuel costs at which nuclear power may be competitive decreases with increasing nuclear plant size. The relatively higher proportion of nuclear power costs which are due to capital costs also makes the comparison somewhat sensitive to the plant capacity factor to be expected and the fixed charge rate considered applicable. The currently estimated levels of fossil fuel costs at which nuclear power could be competitive in the United States, for plants up to 100 MWE, is shown in Figure II.

7. Confidence in the reliability and dependability of nuclear plants of the water-moderated and cooled variety is based upon the record established by the three such plants which have now been operated fairly extensively as power producers on utility systems in the United States. These plants are the pressurized water reactors at Shippingport, Pennsylvania, (Duquesne Light Company System) and Rowe, Massachusetts, (Yankee Nuclear Power Station) and the boiling water reactor at Dresden, Illinois (Commonwealth Edison Company).[8,9]

8. The pressurized water reactor at Shippingport, Pennsylvania, completed two 1000-hour full power (60,000 KWe) runs with the first seed of its seed-blanket core in 1958 and three 1300-hour full power runs with the second seed during 1961. Numerous reactor plant and core tests as well as training exercises were conducted during these intervals. Despite extensive low power operation required for test programs and training during operation with the second seed, gross electric power generation amounted to 514,300,000 kwh - equivalent to operating the plant at full power 70 per cent of the time. Shutdowns for maintenance accounted for less than 3 per cent of the time. The Shippingport station has followed all system load change demands, and has proved it can be shut down and started up under controlled conditions at a faster rate than any modern conventional power plant on the system of the Duquesne Light Company.

9. The Yankee Nuclear Power Station completed operation with its first core on May 18, 1962, after 8600 equivalent reactor hours at 485 MW thermal. During this time gross electric power generation amounted to 1,330,521,000 kwh. This performance is equivalent to operating the plant at full power 68.6 per cent of the time. Plant and core test programs limited the plant load factor, but the reactor was at operating temperature and pressure 90 per cent of the time. The start up of the Yankee plant was accompanied by outages due to steam turbine vibrations and design modifications to the throttle valves and generator control systems. However, only about one week of outage was directly attributable to the nuclear plant, that being due to valve stem leakage.

10. The Dresden Nuclear Power Station has been in service since April, 1960. By September, 1962, gross electric power generation amounted to 1,797,677,000 kwh. There were two unplanned outages attributable to the nuclear plant during this initial operating period. Conditions causing these outages were remedied by design changes to materials in the control rod drives and in the control blades. Following resumption of operation after the outage ending in December, 1961, including the period to September, 1962, reactor availability has been 94.7 per cent, plant availability 92 per cent, and plant capacity factor 85.5 per cent. Since part of the steam in this plant is generated in the core and goes directly to the turbine, it is worth noting that radiation surveys have confirmed experience at the Experimental Boiling Water Reactor and the Vallecitos Boiling Water Reactor, all of which shows only a negligible amount of turbine contamination caused by radioactive corrosion products from the reactor system.

11. Experience with all three of these plants has shown that shielding has been conservatively designed, and radioactive waste release has been far less than permissible limits. Experience also has demonstrated that each of the reactors is capable of much higher outputs than provided in the original design specification. For example, modifications in the Shippingport plant are planned which will increase its output from 68,000 KWE gross to the equivalent of 150,000 KWE gross, using essentially the same pressure vessel but with a one-foot extension in height. The power output from the first core at Yankee was increased progressively from 110 KWE to 141 MWE, and operation with the second core currently is authorized at 155 MWE. The rating of the Dresden plant also progressed from an initial design of 180 MWE to a currently authorized power level equivalent to at least 200 MWE.

12. Operating experience with these major nuclear power producers is continuing to provide the basis for confidence and improvements in future nuclear power plants. More plants representing markedly different technologies are nearing their operating phase. Meanwhile, increased experience and volume in fuel fabrication is providing a basis for commercial fuel cycle guarantees which point toward nuclear fuel cycle costs of the order of 2.0 to 2.5 mills per kwh in the very near future. These figures are expected to drop to 1.0 to 1.5 mills per kwh within 10 years even with accounting practices that would go with private ownership of nuclear fuel, commercial reprocessing, and recycle of plutonium at fuel value.

III. Pattern of Nuclear Power Use in the United States

13. As indicated earlier, the United States has areas representing rather widely differing degrees of development. Therefore, it is of interest to observe the pattern of developing interest in nuclear power. Three different bases for interest in nuclear power are apparent in the United States, excluding interests stimulated by reasons other than evaluation of economic promise.

14. The most prominent basis of interest is in areas which are already highly industrialized to the point where large power plants are warranted but in which fuel costs, for one reason or another, are relatively high. Examples of these areas include the New England States, California and the North Central States.

15. Next, there is interest in providing nuclear power plants on large integrated power grids but located at the periphery of these grids, where the local power demands are still modest and fuel costs are high because of relative remoteness of the site from fuel resources. This situation is examplified, for example, by the Big Rock Point Plant of Consumers Power of Michigan and by the Pathfinder Plant of Northern States Power Company.

16. Finally there is interest in nuclear power in very isolated places, even though quite small plants might be required. The outstanding example of this application by the United States is the location of a nuclear power plant of 1500 KWe capacity at McMurdo Sound, and plans for installation of similar small plants at other sites in Antarctica and elsewhere.

17. Each of these three types of interest is soundly based in terms of attempting to provide most effective use of available energy resources with consideration of the many factors involved in making such evaluations.

18. The long term interest of the United States in nuclear power development is to make possible the realization of the full energy potential of nuclear fuels and thus to make it possible for these fuels to provide the nation's power needs for many centuries. Projections of power requirements against various fuel resources indicate that early in the twenty-first century the United States should be prepared to have all new increments of power generating capacity supplied from nuclear plants.

IV. Bases for Interest in Less Developed Countries

19. The World Power Conference Survey of Energy Resources, 1962[13] summarizes the situation on total energy resources as follows:

> ".....it is interesting to estimate the coal equivalent of the reserves of the fossil fuels - coal, brown coal and lignite, peat, petroleum, oil in shale and bituminous sand, and natural gas - that could probably be economically recovered. The coal equivalents are 3 million million tonnes for coal, brown coal and lignite, 100,000 million tonnes for peat, 90,000 million tonnes for petroleum, 200,000 million tonnes for oil in shale and bituminous sand, and 90,000 million tonnes for natural gas or a total coal equivalent of about 3.5 million million tonnes for all these resources. This quantity is 700 to 800 times the coal equivalent of the whole of the fuel and energy used annually by the world at the present time.....
>
> "In addition, there are the enormous amounts of energy to be derived from nuclear fission and probably also from nuclear fusion.....
>
> "It is thus clear that for the world as a whole there is no shortage of energy. The problem is one of economics. Costs must differ considerably in different areas owing to the uneven distribution of resources and the heavy costs often involved in the transport of materials and energy in their various forms....."

20. The ratio of fossil fuel reserves to the current rate of consumption is put in somewhat different perspective when one recognizes that highly developed areas have a per capita energy consumption rate of about 6 times the world average and that electric power consumption rates in general are doubling approximately every 10 years. Thus, if all areas were using energy at the same rate as the United States, for example, and if growth rates continued as at present, the fossil fuels referred to above would be adequate for only three or four decades - comparable to the expected lifetime of a power plant.

21. For the short term the emphasis clearly must be a choice among the alternative fuels to provide the most favorable economics - which, in turn, if properly evaluated, implies the most effective use of resources. The analysis necessary to make that choice generally is not a simple one. It must be made for specific situations by persons having intimate knowledge of pertinent local factors and persons with expert knowledge of the most modern technologies related to the use of the alternate fuels. Enlightened consideration of nuclear power in such evaluations has been greatly aided by the work of the International Atomic Energy Agency, which, in response to requests of various countries, has sent special missions of qualified people to study local situations. Each of these studies results in a fairly detailed report.[14,15,16] Other important studies of this type have been done by individual countries and at least in some areas, such as India and Brazil, it has been determined that nuclear power is economically attractive now. It is not possible in this paper to do a satisfactory job of digesting the various reports on the applicability of nuclear power for less developed areas, yet these areas represent only a small fraction of those which warrant study. A few general observations can be made, however, which may be helpful in determining whether or not more serious studies are warranted and in avoiding premature optimism and enthusiasm.

(a) Fossil fuel costs which appear to be high may be artificially imposed; while consideration of nuclear power in these cases may lead to reduction in fossil fuel prices, construction of the nuclear plant may not be economically justified when realistic fossil fuel costs are reflected.

(b) High power costs due to small plants operating a relatively small fraction of the time are not likely to be an attractive situation for nuclear power.

(c) Nuclear power looks most favorable in areas in which other fuel resources are exhausted or are basically costly to provide and which, at the same time, require reasonably large sized plants having power requirements that warrant operation of the plant a large fraction of the time. Thus, the first applications of nuclear power may properly be in the more highly industrialized areas of so-called "less developed" countries.

(d) Nuclear power, because of its minimum requirements for logistic support, may permit economically favorable development of natural resources in areas without established extensive transportation networks or with environmental impediments. This is particularly true if the situation is such that extensive transportation networks can be avoided by on site processing.

(e) Nuclear power and the potential hazards of radiation associated with it will undoubtedly require special attention to the establishment of national policy and legislation, and to the education of the public in order to obtain public understanding and acceptance. The effects of potential hazards in terms of national policies and public liability may not be susceptible to adequate treatment in an economic evaluation.

(f) The relative requirements of different power systems for foreign exchange can be more important in the final choice than would be evidenced by economic evaluations based on normal currency exchange rates.

22. The probable impact of nuclear power on foreign exchange requirements merits further discussion. Consider, for example, an area in which it appears that installation of a million kilowatts may be justified in the 1970's. This situation could be applicable to many of the currently less developed countries because of the large expansion in power generating capacity which may be anticipated. Present cost estimates indicate that if this capacity of one million kilowatts was installed in units of 50-150 MWE, each choice of nuclear plants, based on current experience in the United States, would result in an increase in capital cost of approximately 100 million dollars.

23. It is not likely, of course, that the total incremental cost would require foreign currency. The actual amount required would be subject to detailed negotiations

between the buyer and the seller. It seems reasonable, however, based on experience to date, to expect that less than half of the incremental cost would require foreign exchange except for a country which has little or no industrial capability in which case, up to three-fourths of the incremental cost would require foreign exchange. For each mill/kwh saved in fuel cost, the nuclear plants would yield a saving of about 5 million dollars per year. Savings of 2 or 3 mills/kwh in fuel cycle costs seem quite possible. If all fuel (fossil or nuclear) would have to be imported into the area, fuel savings from the nuclear plant could yield reductions in foreign exchange requirements of perhaps as much as 15 million dollars per year.

24. In addition, there is the possibility of developing an industrial capability to perform some of the nuclear fuel cycle operations, thus further reducing foreign exchange requirements. The greatest potential in this area is for eventual development of fuel preparation and fabrication of fuel elements. This part of the fuel cycle could correspond to about 1 mill/kwh, or another 5 million dollars annually for the million KW installed capacity assumed. The prospects for local reprocessing of irradiated fuel at this level of capacity (corresponding to less than 100 tons per year of spent fuel from reactors fueled with slightly enriched uranium) does not look promising. Similarly, the U-235 enrichment capacity required probably would be too small to be economically attractive. It is very likely, however, that reprocessing services for irradiated fuel will be available in countries with larger nuclear power installations, also fuel enriching services will be available on a toll basis, so that full advantage can be taken of purchasing natural uranium on a competitive market. Also, by the 1970s technology is expected to make economically practical the use of plutonium[17] produced in the reactor to minimize the requirements for separative work for U-235 enrichment.

25. It is possible, of course, to defer the need for enriching uranium and reprocessing irradiated fuel by using power reactor concepts which will operate on natural uranium. There is no question but that such plants can be built and can be made to operate reliably and dependably. Again, it should be possible to make the choice primarily on the basis of comparative economics. Capital costs for nuclear plants using reactors designed to operate on natural uranium are relatively more sensitive to the plant capacity than other nuclear power plant systems. This is shown in Figure III, which gives the effect of size upon the unit capital cost for the D_2O-natural uranium and the H_2O-slightly enriched uranium plants based upon best available estimates for plants which could be built today.[18,19,20]

26. The higher unit capital costs for the D_2O-natural uranium plants given in Figure III can be explained by (a) the high investment in D_2O required, (b) the need for somewhat larger cores for natural uranium reactors, and hence larger investment in reactor plant, for the same power output, and (c) the stage of development of the two concepts. While the capital cost differential may approach zero in very large plants (probably above 500 MWE) as more construction experience is obtained in building D_2O plants, at the present there appears to be a capital cost differential (exclusive of heavy water) of about $160/KWE in sizes of the order of 100 MWE. The cost of heavy water at the current price of $61.60/Kg will add approximately $80/KW - this generally will increase the seriousness of any foreign exchange problem. The net effect of these capital cost differentials depends upon the fixed charge rate used, plant capacity factor, and various other factors. Even under low fixed charge rates, often associated with public financing, these capital cost differentials are equivalent to above 2 mills/kwh. Rates associated with private financing would about double this effect. This incremental cost difference in mills/kwh for the capital and fuel is indicated in Figure IV. For these comparisons heavy water moderated plants are taken as being at least as favorable economically as other natural uranium fueled plants. Graphite moderated systems avoid the cost of heavy water but are physically larger and reactivity limitations shorten the fuel irradiation cycle, tending to increase fuel costs.

27. Fuel cycle costs for all reactors increase with decreasing size because of neutron leakage, which results in relatively short fuel exposures for natural uranium fueled plants and relatively higher enrichments for reactors which take advantage of fuel enrichment. The estimated fuel cost as a function of plant size for the D_2O-natural and H_2O-enriched plants is also given in Figure IV.

28. The residual value of the fuel discharged from enriched uranium reactors is considerably higher than the cost of the shipment to a processing facility and the processing charges. In this respect it should be noted that, for a shipping charge of $15/KgU and a processing charge of $30/KgU, the contribution of these charges to the generating cost is less than 0.5 mill/kwh because of the high burnup of fuel (15MWD/KgU) which can be achieved in reactors using slightly enriched fuel. While there may be somewhat higher shipping charges for return of fuel from, for example, a country several thousand miles from the processing facility, this incremental cost would not be expected to increase the generating cost more than 0.1 mill/kwh over cost estimates based upon shipment within the United States. In the case of natural uranium reactors, shipping and processing charges for these distances would be expected to exceed the fuel value of the discharged nuclear fuel. Here, the discharged fuel could be stored until a more economically favorable situation developed as regards fuel processing or value of plutonium in the spent fuel.

29. The costs which have been presented in this paper refer in most part to costs in the United States. Specific estimates would be required in order to determine what the costs would be in specific less-developed nations. In general, in spite of the possible lower wages in the less-developed countries, it is to be expected that there will be off-setting costs for skilled foreign technicians, training and organization of domestic skills, and transport of plant components, so that the cost of installing a nuclear plant in a less-developed country will be higher than for the United States. The situation is the same for a conventional fossil fueled station.

30. The United States will continue to give wide dissemination to information developed in its extensive nuclear power program and will endeavor to provide such other assistance as may be helpful in arriving at a sound conclusion on the merits of nuclear power in specific countries.

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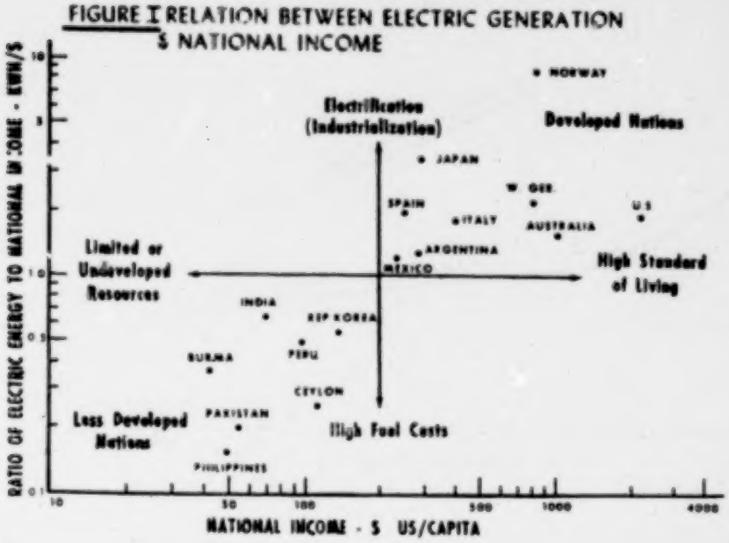

FIGURE I RELATION BETWEEN ELECTRIC GENERATION & NATIONAL INCOME

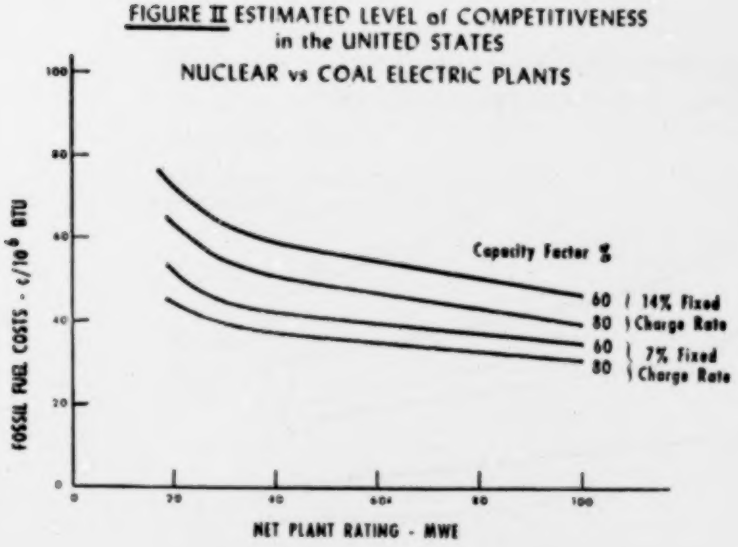
FIGURE II ESTIMATED LEVEL of COMPETITIVENESS
in the UNITED STATES
NUCLEAR vs COAL ELECTRIC PLANTS
FOSSIL FUEL COSTS - ¢/10⁶ BTU
Capacity Factor %
60 } 14% Fixed
80 } Charge Rate
60 } 7% Fixed
80 } Charge Rate
NET PLANT RATING - MWE

FIGURE II ESTIMATED LEVEL OF COMPETITIVENESS
IN THE UNITED STATES
NUCLEAR vs COAL ELECTRIC PLANTS

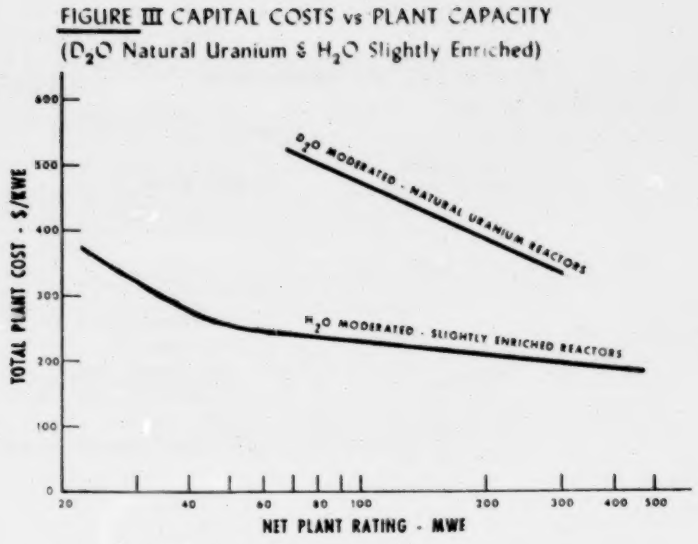

FIGURE III CAPITAL COSTS vs PLANT CAPACITY
(D_2O Natural Uranium & H_2O Slightly Enriched)

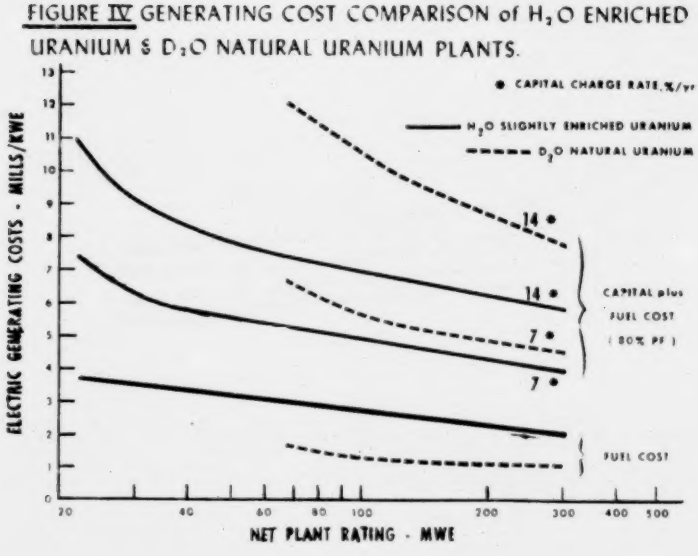

FIGURE IV GENERATING COST COMPARISON OF H_2O ENRICHED URANIUM & D_2O NATURAL URANIUM PLANTS

1773 E - Nov. 1962 - 1,600